LIDAR AND AIRBORNE INVESTIGATION OF SMOKE PLUME CHARACTERISTICS: KOOTENAI CREEK FIRE CASE STUDY

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ABSTRACT

A ground-based scanning lidar was utilized with a set of airborne instruments to acquire measurements of smoke plume dynamics, smoke aerosol distribution and chemical composition in the vicinity of active wildfires in the western U.S.

A new retrieval technique was used for processing lidar multiangle measurements. The technique determines the location of atmospheric heterogeneity versus height, which is retrieved from the entire vertical scan taken from a selected azimuthal direction. The vertical profiles of smoke plumes derived from heterogeneity events detected from lidar are consistent with aerosol mass concentrations, derived from airborne measurements in smoke plumes.

The measurements are made with the purpose of acquiring the data necessary for the evaluation of plume rise and smoke dispersion models.

1. INTRODUCTION

Biomass burning can significantly degrade regional air quality. Land management agencies and air quality regulators require rigorously tested, accurate smoke dispersion models to quantify the contribution of biomass burning emissions to air pollution. Accurately describing and predicting the dynamics of smoke plumes and subsequent smoke transport is a major uncertainty in determining the impact of fire emissions on regional air quality.

Plume rise models for biomass fires are used to prescribe the vertical distribution of fire emissions, which are critical input for smoke dispersion and atmospheric chemistry transport models. However, the ability of plume rise models to accurately capture the plume behavior of biomass fires is highly uncertain. The plume rise predicted by different models can be quite variable for a given fire.

An example of discrepancies between models is given in Figure 1, which shows hourly plume rise heights (ΔH) predicted by three different models for the Bugaboo Fire in Georgia, U.S.A. on May 8, 2007. In this instance, the models differ in both the predicted plume rise height and the temporal pattern.

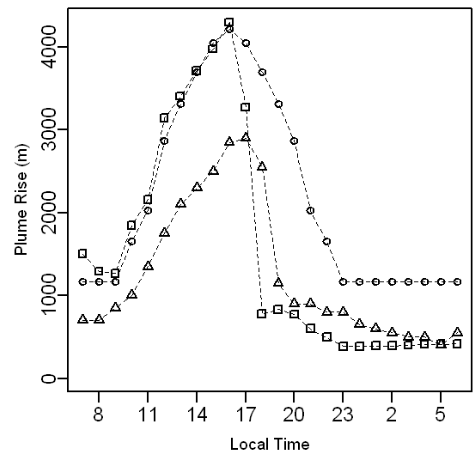

Figure 1. Plume rise height (ΔH) predicted by three models for the Bugaboo Fire in Georgia, U.S.A. on May 8-9, 2007. The models are: Briggs equations [1] (squares), Harrison and Hardy empirical model [2] (circles), and PLUMP [3] (triangles).

While many plume rise models and smoke dispersion models exist, few observational datasets are available to properly validate these models and quantitatively assess their uncertainties, biases, and application limits.

We have initiated a research project to address this critical observation gap. Its purpose is to acquire the data needed for evaluation of plume rise and smoke dispersion models. The project deploys a ground based, mobile lidar instrument with a set of airborne instruments to acquire measurements of smoke plume dynamics, smoke aerosol distribution and chemical composition in, and around, the plumes of active wildfire and prescribed fire events in the western U.S. The lidar measures plume dimensions and aerosol optical properties. The airborne instrument package, deployed on a Cessna aircraft, measures the distribution of aerosol mass concentration and the concentrations of the major trace gases emitted by fires (CO, CO_2, and CH_4). We present the experimental results of a case study of smoke plume characteristics over the Kootenai Creek Fire in Montana from late July to August 2009.

2. INSTRUMENTATION

2.1 Lidar

For ground measurements, we used the mobile scanning lidar developed at the Missoula Fire Sciences Laboratory. The lidar uses the Nd:YAG laser and operates on two wavelengths, 1064 nm and 355 nm, with the pulse energy 98mJ and 45mJ, respectively. The beam divergence is 1 mrad. The receiver includes the Cassegrain 10 in. diameter telescope and two detectors – the IR-enhanced Si avalanche photodiode (1064 nm) and the photomultiplier (355 nm). The scanning capabilities of the lidar allow changing the searching direction rapidly to 180^o horizontally and 90^o vertically.

In principle, lidar can easily detect the boundary between different atmospheric layers. Subjective visual identification of heterogeneous areas, such as the atmospheric boundary layer or clouds, in lidar scans is simple. However, the use of an automated method to select these boundaries is a significant challenge. Generally, the heterogeneous boundaries in the atmosphere are not well defined, especially in smoke plumes, where the dispersion processes create a continuous transition zone between clear air and the dense part of a plume.

We developed a method for processing the lidar vertical scans obtained in areas of smoke plumes and extracting information on plume heights and their spatial and temporal changes. The technique determines the location of atmospheric heterogeneity versus height for every vertical scan made in a fixed azimuthal direction. To achieve this goal, the normalized intercept function [4],

$$Y_{0,norm}(x,\varphi) = \frac{\left| Y_\varphi - \frac{dY_\varphi}{dx_\kappa} x_\varphi \right|}{x_\varphi + \Delta_\varphi} \qquad (1)$$

is calculated, where

$$Y_\varphi = [P_\varphi(x_\varphi) + B_\varphi] x_\varphi . \qquad (2)$$

Here φ is the slope direction searched by the lidar, $P_\varphi(x_\varphi)$ is the backscatter signal measured at the range r_φ , the variable $x_\varphi = r_\varphi^2$, B_φ is the constant offset of the recorded signal created by a daytime background illumination and electrical or digital offset, and Δ_φ is a constant. The functions $Y_{0,norm}$ (x, φ), recalculated into the corresponding functions of the height, h, are determined for the entire set of slope directions φ and then averaged. The next procedure transforms the averaged function, $Y_{0,norm}(h)$, into what we define as the Atmospheric Heterogeneity Height Indicator (AHHI). The AHHI is a histogram, which shows the number the heterogeneity events, that is, the number of the slope directions of the scanning lidar in which the atmospheric heterogeneity was established for the consecutive height intervals [5].

Using the AHHI algorithm, the maximum plume rise can be derived from a large volume of lidar data to provide an accurate time series profile of smoke-plume heights.

2.2 Airborne instrumentation

Lidar is a powerful tool for measuring the dimensions of smoke plumes, especially plume rise height ΔH. However, lidar alone cannot provide the observations required to evaluate smoke dispersion models because of limited measurement range and the inability to measure smoke aerosol mass concentrations. When airborne sampling maneuvers, such as vertical profiles and horizontal transects, are executed near and downwind of active fires, the airborne instrumentation can measure trace gas and aerosol concentrations in smoke plumes.

The primary airborne instrument deployed in this study is a Radiance Research nephelometer (model 903). Nephelometers measure light scattering by aerosol, which can be related to aerosol mass concentration by a mass calibration curve. Prior to field deployment, a set of experiments were conducted at a large-scale combustion chamber in our laboratory for calibrating the Radiance Research nephelometer. A total of 19 chamber burns were conducted using wildland fuels characteristic to the northwest U.S. – fir branches with needles attached and/or ponderosa pine needles. The experiment used a filter sampling system that drew sample at 30 Lpm through dielectric tubing to a cyclone with a 2.5 μm cut-point, then onto a Teflon filter. The Teflon filters were conditioned (for a minimum of 24 hours) and weighed in a controlled environment room on a Mettler M4 microbalance with a precision of 1 μg. The filter sampling system and analysis protocol had been previously validated versus Federal Reference Method (FRM) PM2.5 air samplers (the BGI, Inc. PQ200 and the Partisol FRM Model 2000) [6].

The calibration data points and resultant nephelometer calibration curve are shown in Figure 2. The average aerosol mass concentration for an experiment was derived from the aerosol filter mass loading, the filter sample volumetric flow rate, and the total sample duration time. As may be seen in Figure 2, the average nephelometer scattering is highly correlated with the aerosol mass concentration (r = 0.96). This calibration curve may be used to estimate aerosol mass concentration from the nephelometer measurements of light scattering in fresh smoke produced by fires consuming conifer forest vegetation.

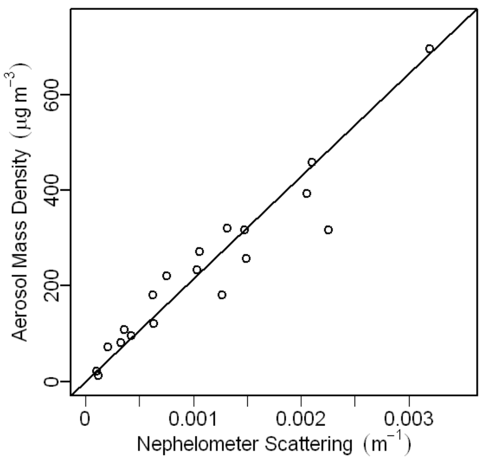

Figure 2. Calibration of the Radiance Research nephelometer. The solid line is the linear least-squares best-fit with zero intercept. The slope is 214,800 (±9200) μg m^{-2} (uncertainity 1σ), r^2 =0.97.

3. EXPERIMENT AND RESULTS

We investigated smoke plume characteristics over the Kootenai Creek Fire in Montana, U.S.A., for 7 days in late July and August of 2009. Between mid-July and early September, the fire burned ~2,000 ha of conifer forest. Measurements of plume rise, smoke dispersion, and chemical composition were performed with the mobile lidar and airborne instruments.

The fire location, aircraft flight path, measured aerosol mass concentration, and lidar scan directions on August 27 are shown in Figure 3.The aircraft flight path included two 30 km segments, oriented perpendicular to the transport winds (i.e., the direction of the plume flow) and located ~ 10 km downwind of the active fire. The flight segments were conducted at elevations of 1900 m and 2500 m above ground level. The aircraft sampling also included a vertical profile taken ~ 10 km downwind of the active fire.

Figure 4 presents the vertical profile of the aerosol mass concentration measured during the airborne sampling. Two important features are apparent in this figure. First, the smoke plume has a well-defined upper boundary close to the height of 2800 m. Second, the smoke concentration is highly variable, creating some local inhomogeneous areas within the area of the smoke plume.

Examples of the retrieved lidar data taken at the 1064 nm wavelength are shown in Figures 5 and 6. The results of lidar scanning over three azimuthal directions, 105^o, 125^o, and 140^o are shown, taken at

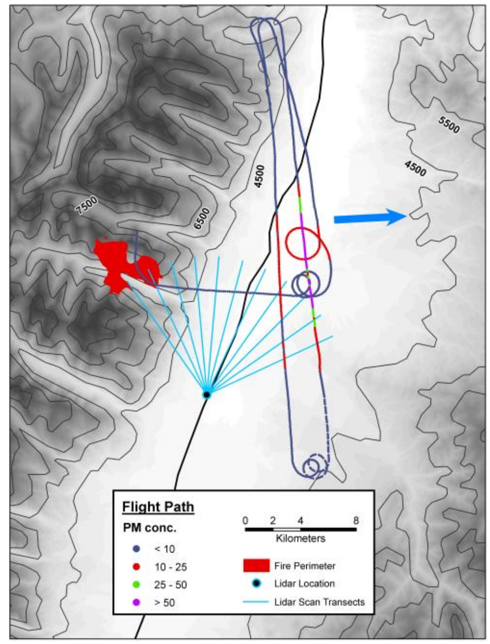

Figure 3. Flight path with measured aerosol concnetration, lidar deploment location, lidar scan directions, and fire perimeter.

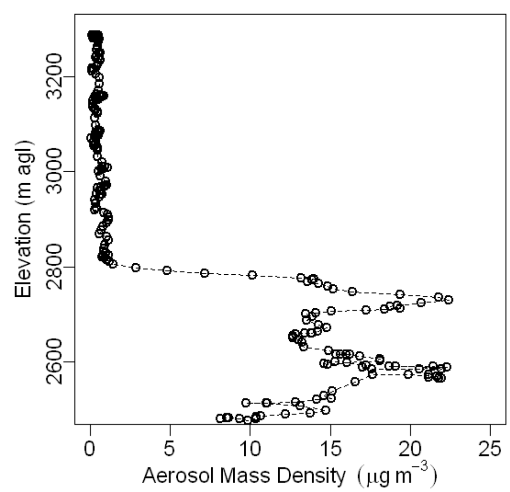

Figure 4. Vertical profile of aerosol mass concentration measured ~10 km downwind of the Kootenai Creek Fire. The vertical profile clearly identifies the top of the smoke plume located ~2790 m.

15:39 PM, 15:47 PM, and 15:54 PM, respectively; each vertical scan took ~ 2 min. Three polluted regions can be distinguished within the altitudes from ground level up to the height of ~3000 m: the polluted air from ground level to ~700 m, the smoke plume over the height interval from ~ 700 m to

~2000 m, and between ~2000 m – 3000 m. The same regions can be identified in Figure 6, where the corresponding AHHI calculated with the level 0.2 are shown. The horizontal line in the figure shows the smoke boundary height 2790 m from the airborne observation at 15:55 PM, which is consistent to the lidar observations.

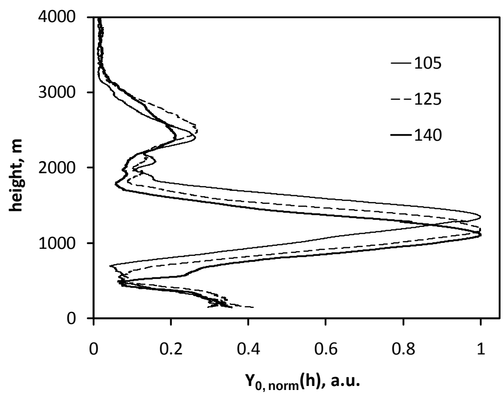

Figure 5. The averaged and normalized functions, $Y_{0,norm}(h)$, determined for the azimuthal directions ψ = 105°, 125°, and 140°.

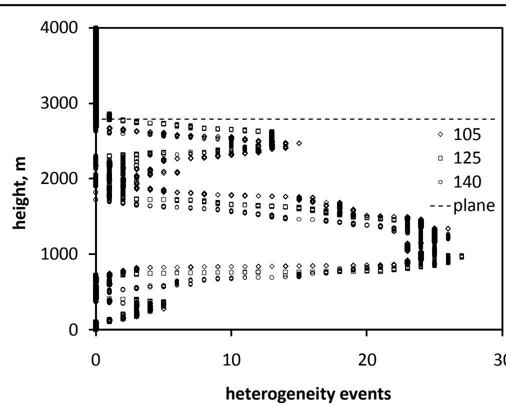

Figure 6. Plots of Atmospheric Heterogeneity Height Indicator calculated for the same azimuthal directions as in Figure 5.

4. SUMMARY AND FUTURE WORK

We have successfully acquired measurement datasets that may be used to rigorously evaluate plume rise and smoke dispersion models. The approach combines mobile ground-based lidar with airborne instruments for measuring plume heights and aerosol mass concentrations over the 2009 Kootenai Creek forest fire in Montana, U.S.A. We applied the recently developed methodology to study the smoke plume heights and their spatial and temporal changes from lidar vertical scans. The vertical profiles of smoke plumes derived from heterogeneity events detected from lidar and aerosol mass concentrations measured from airborne measurements are consistent.

We will deploy the mobile scanning lidar and airborne instruments to wildfires in the western U.S. in the summer of 2010. The observations will be used to validate plume rise heights predicted by models such as Daymsoke [7], PLUMP [3], and the Briggs equations [1]. These plume rise models, along with similar models, are used to determine the vertical distribution of fire emissions that are critical input for smoke dispersion and atmospheric chemistry transport models. The aerosol mass concentrations measured by airborne nephelometer will be used to validate the aerosol fields simulated by high-resolution smoke dispersion models.

5. REFERENCES

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